

Analysis strategies and software for geodetic VLBI

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Abstract. This article describes currently used analysis strategy and data analysis software for geodetic VLBI. Today's geodetic observing strategies are shortly presented, and the geodetic VLBI observables and data modeling are briefly discussed. A short overview is given on existing geodetic VLBI software packages and the statistical approaches that are applied. Necessary improvements of today's analysis software are described. Some of the future expectations and goals of geodetic VLBI are presented and the corresponding consequences for the VLBI technique are explained. This includes consequences in terms of technical development and corresponding improvements in data modeling and analysis software.

1. Introduction

Since 1999 the International VLBI Service for Geodesy and Astrometry coordinates and schedules global geodetic VLBI sessions (Schlüter et al. 2002). It applies observing strategies that aim at exploiting the available resources for geodetic VLBI in a best possible way in order to reach today's research goals. These observing strategies are briefly described in Section 2.

The IVS analysis centers apply analysis strategies and use analysis software that allow to analyze today's geodetic VLBI observables as good as possible. This is shortly described in sections 3 to 6. Using these approaches important scientific results can be derived from the geodetic VLBI data analysis.

However, further improvements for example in modeling of geophysical effects and error sources are necessary in order to gain further insights in today's research achievements. These are described briefly in Section 7.

Furthermore, in order to reach new research goals, technical improvements of the geodetic VLBI technique and the corresponding improvements in data modeling, analysis software and analysis strategy are necessary. They are described in sections 8 and 9.

2. Geodetic VLBI observing strategies

The IVS coordinates and schedules global geodetic VLBI observing sessions. This is done in agreement with the contributing partner organizations, i.e. the international radio astronomical observatories and the correlators that are active in geodetic VLBI. The main objectives of the coordinated observation sessions are contributions to reference systems and their relations, i.e. the International Terrestrial Reference Frame (ITRF, e.g. Altamimi et al. 2002) the International Celestial Reference Frame (ICRF, e.g. Ma et al. 1998), and time series of Earth Orientation Parameters (EOP). Currently, dedicated observation sessions are scheduled that are optimized for the different goals. The available resources in terms of radio telescopes and correlator capacity act of course as constraints.

The IVS schedules multi-station sessions for EOP determination twice a week. Here large and distributed networks of currently up to eight stations perform observations for 24 hours. The full set of EOP components, i.e. corrections to the

nutration model, polar motion components and the earth rotation component UT1, can be determined from the data analysis of these observation sessions.

Daily short sessions are scheduled to observe at least the earth rotation component every weekday. For these sessions only two stations that form an extended east-west baseline observe for two hours.

Multi-station observation sessions for the ITRF and the ICRF are scheduled several times per year with large and distributed networks and observing time of 24 hours.

These observing strategies exploit today's existing resources for geodetic VLBI in a nearly optimum way. However, from a scientific point of view it would be desirable to use a more holistic approach and to optimize the observations sessions in a way that all parameters of interest can be determined simultaneously. This means that the geodetic VLBI technique has to be developed further and for example the number of observing instruments has to be increased (Petrachenko et al. 2004).

3. The geodetic VLBI observables

A successful correlation of geodetic VLBI observations results in phase delay and group delay observables. The use of the phase delays for geodetic purposes is complicated because of loss of phase coherence between different scans due to instrumental and environmental influences (Campbell 2000). Geodetic VLBI observation schedules are usually optimized for sky coverage, i.e. observing the widest possible distribution of radio sources over the sky per time interval. This scheduling strategy is applied in order to be able to successfully determine the geodetic parameters of interest in these time intervals. The drawback is that the telescopes move over large slewing ranges and phase coherence between succeeding scans is lost.

So far it has not been completely successful to use phase delay in geodesy (Herring 1992, Petrov 1999). Thus, only the group delay observables are analyzed routinely. The precision of the group delay observables is today on the level of 10 ps (Sovers & Fanselow 1998). This precision is currently not high enough to reach the goal of long-term accuracy of geodetic reference frames at the level of 1 mm or below. Therefore the

geodetic VLBI technique needs further development that allows to increase the delay precision (Petrachenko et al. 2004).

4. Data modeling

Any analysis of observed data of course requires also data modeling which is based on theoretical models and a priori information. The modeling of so-called theoretical observations and the application of statistical analysis methods form the basis to derive the parameters of interest. For geodetic VLBI this means that the group delay observables have to be modeled accurately (e.g. Sovers & Fanselow 1998).

The geometric delay is the largest component of the observed group delay. It is modeled in a quasi-inertial solar system barycentric (SSB) frame based on a priori information of the proper station locations and the direction to the observed radio source.

Before the geometric delay in the SSB can be calculated, the proper locations of the stations given in the earth fixed frame have to be transformed to the SSB frame. Station displacements due to plate tectonics, solid earth tides, pole tide, ocean tide loading, and atmospheric loading need to be modeled. The two frames involved have to be aligned using the state of the art precession-nutation model and a priori information about polar motion and earth rotation and the corresponding tidal variations of the EOPs. The transformation from a geocentric to a barycentric frame is performed by a Lorentz transformation and includes relativistic effects. Then the geometric delay can be calculated and corrected for general relativistic effects and transformed to a proper delay. This delay is transformed back to a geocentric frame via a Lorentz transformation.

The propagation of the radio waves through the earth's atmosphere also has to be considered. The ionospheric contribution is usually corrected for based on the dual-frequency observations at S- and X-band. The tropospheric delay is usually modeled a priori based on local pressure observed at the stations and the corresponding mapping functions. Today still widely used mapping functions use season, latitude and altitude as input parameters (Niell 1996).

More details on data modeling can for example be found in Sovers & Fanselow (1996) and Sovers et al. (1998). The data modeling as described above should in general follow the recommendations of the International Earth Rotation and Reference Systems Service (IERS) that are formulated as so-called IERS Conventions. These form a common and consistent basis for all different geodetic space techniques to allow comparisons and combinations of the results derived from these techniques in a meaningful way.

5. Analysis strategies

It is common use in geodetic VLBI analysis, and also in other geodetic space techniques, to distinguish between so-called arc parameters and global parameters. This distinction reflects the time epochs for which the parameters are valid.

Arc parameters are parameters that are valid only during a particular observation session or parts of it. Examples are pa-

rameters that describe the turbulent troposphere, relative clock parameters, and the earth orientation parameters that relate the earth-fixed and quasi-inertial reference frames.

Global parameters are on the other hand valid for longer time period and not only for the actual observing session. For example radio source coordinates, relativistic parameters, and station coordinates and velocities belong to this category of parameters.

A so-called single-session analysis uses only VLBI observables of one session of usually 24 hours duration. With this approach only arc parameters can be accurately determined. This means that for example the station coordinates and radio source positions are kept fixed at their a priori values and the EOP's are determined from the data analysis. Of course also tropospheric and clock parameters have to be estimated. With this strategy it is possible to derive EOP for individual observing sessions and thus finally a time series of EOP.

It is also possible to derive time series of relative station positions using the single-session approach. In this case the a priori EOP and radio source positions are kept fixed and relative station coordinates and tropospheric and clock parameters are determined. These relative station coordinates are of course valid only for the epoch of the observation session. In a second analysis step using the time series of relative coordinates, also relative station velocities can be determined (e.g. Haas et al. 2003).

A so-called global analysis uses a large number of VLBI sessions together and allows to solve for both arc and global parameters. One possible approach is to accumulate reduced normal equations from single sessions that no longer contain arc parameters, and then to solve for the global parameters. After that the arc parameters for each session can be determined in a second step by substituting the estimated global parameters. Another possible approach is to combine the variance-covariance matrices of individual observing sessions with filtering techniques and to determine stochastic parameters in a smoothing approach (Andersen 2000).

Some interesting results from global analysis are for example investigations of the free core nutation (Herring et al. 1986), tidal effects in the earth rotation (Brosche et al. 1991), ocean tide loading (Sovers 1994), frequency dependent Love and Shida numbers (Haas & Schuh 1996), the ICRF (Ma et al. 1998), atmospheric loading (Petrov & Boy 2004), and general relativity (Shapiro et al. 2004).

6. Data analysis software

A number of geodetic VLBI data software packages have been developed during the last decades. Table 1 is an attempt to give an overview of these software packages, though not claiming completeness. Unfortunately, not all software packages are documented in an easy accessible way. Some of the packages have stopped maintenance and development, e.g. VORIN, others are still in a process of development, e.g. QUASAR. It appears that currently the VLBEST software package is the only one to allow automated real-time data analysis, as demonstrated in the Japanese Keystone project (Koyama et al. 1998). The two software packages GEOSAT and GINS were devel-

oped with the aim to integrate VLBI data analysis with data analysis of other geodetic space techniques at the observational level.

In general, the software packages aim at following some general modeling advice for geodetic space techniques that has been agreed on in the geodetic community and is formulated in the IERS Conventions. Most software packages claim to comply with the IERS Conventions 1996 (IERS 1996), and several are on the way or have already updated to the IERS Conventions 2003 (IERS 2003).

Some inter-comparison tests between individual software packages have been performed in the past (e.g. Sovers & Ma 1985). However, so far there has not been a common comparison between all software packages.

The software packages use various statistical methods for the actual data analysis. These statistical methods include the Least-Squares (LSQ) method (e.g., Koch 1988), the Kalman-filter (KF) method (e.g. Kalman 1960), the Square-Root Information Filter (SRIF) (Bierman 1977) and the Least-Squares Collocation (LSQC) method (e.g. Koch 1988, Moritz 2000). These statistical approaches differ mainly in the way the variance-covariance information is propagated and the ability to treat stochastic parameters.

Most of the software packages aim at allowing portability to a large number of computer platforms and operating systems. However, this goal has so far only been reached for very few cases and still some dependency on computer platform and operating system exists. For example the widely used software package SOLVE is still only available for HP machines and HP-Unix operating systems.

The software packages still use different data input formats. Both binary and ASCII data formats are in use and the necessary conversion software exists. However, a working group of the IVS tries to establish a common exchange format called PIVEX (Gontier & Feissel 2000).

Currently there are 7 full IVS analysis centers and 14 associated analysis centers. The CALC/SOLVE software is used

by 9, OCCAM by 4, and MODEST by 2, while GLORIA, GEOSAT, VLBEST, SOLVK, and STEELE-BREEZE are each used by one analysis center only.

7. Necessary improvements today

Although important results can be derived from today's geodetic VLBI data analysis, further improvements in particular in the fields of data modeling and statistical methods are necessary. These improvements are needed today and independent of possible technical modifications of the geodetic VLBI technique that might lead to higher precision of the observables.

Some of the current limitations on the modeling side are due to insufficient atmospheric modeling. Mapping functions based on Numerical Weather Models (NWM) promise to lead to improvements (Boehm and Schuh 2004, Stoyanov et al. 2004). An even more interesting approach might be to apply direct raytracing through NWM instead of using mapping functions. Also modeling based on turbulence theory appears to be an interesting approach (Emardson & Jarlemark 1999). Thus, the data analysis packages should be extended to incorporate these approaches.

Another concern of improved data modeling is radio source structure. In the ideal case the radio sources observed for geodetic VLBI would all be structureless compact objects, i.e. point sources. However, there are many sources that show considerable structure at X-band (Fey & Charlot 1998, 2000). Thus, there is a need to model the source structure effects and to incorporate this in the geodetic VLBI data analysis. So far this is not done on a regular basis and therefore the software packages have to be extended to be able to do so. This is true even for the case that future geodetic VLBI observations might use higher frequencies with less structure, since it has to be guaranteed that the historic observations can be re-analyzed in the best possible way.

Periodic station displacements due to solid earth tide and ocean tide loading effects are modeled routinely and with high precision in today's data analysis. However, non-periodic station displacements due to atmospheric and hydrological loading or local deformation of the telescopes as a function of temperature, are not yet treated routinely. It appears that atmospheric loading can be modeled with sufficient accuracy based on convolution of global pressure data (Scherneck et al. 2002, Petrov & Boy 2004). Thus, the modeling of this phenomenon should be incorporated in all data analysis software packages. Hydrological loading is more difficult to model mainly because the hydrological models are still restricted in accuracy. Therefore this loading effect will still be a topic of investigation for the future.

Thermal deformation of radio telescopes is today monitored routinely at two of the radio telescopes used for geodetic VLBI observations. A simple model to describe the thermal deformation effect is presented in the IERS Conventions 2003 (IERS 2003). However, so far neither the actual deformation measurements nor the model is used routinely in all data analysis packages. More advanced modeling based on finite element calculations promises to allow modeling for any kind of tele-

Table 1. Geodetic VLBI data analysis software packages.

| Software package | Statistical Method* |
|-----------------------------------|---------------------|
| CALC/SOLVE (Ma et al. 1990) | LSQ |
| OCCAM (Titov et al. 2002, 2004) | LSQ/KF/LSQC |
| MODEST (Sovers & Jacobs 1996) | SRIF |
| SOLVK (Herring et al. 1990) | KF |
| STEELE-BREEZE (Bolotin 2000) | SRIF |
| GLORIA (Gontier, 1992) | LSQ |
| VLBEST (Koyama et al. 1998, 1999) | LSQ |
| GEOSAT (Andersen 1995, 2000) | KF |
| VORIN (Petrov 1995) | LSQ |
| ERA (Krasinsky & Vasyliiev 1997) | LSQ |
| GINS (Meyer et al. 2000) | LSQ |
| QUASAR (Gubanov et al. 2004) | LSQC |

*The abbreviations used for the statistical methods are:

LSQ – Least-Squares method, SRIF – Square-Root Information Filter, KF – Kalman Filter, LSQC – Least-Squares Collocation method. See text for further explanation.

scope (Clark & Thomsen 1988) and might be incorporated in the data analysis in the near future.

Currently there are also limitations in the statistical part of the data analysis. The existing data analysis packages differ concerning the statistical methods that are applied and how stochastic parameters are treated. It appears that in some cases there are deficiencies in particular in the handling of covariances between different parameters (Tesmer & Kutterer 2004). Thus, the software packages should be extended and more refined stochastic models should be incorporated.

8. New scientific goals

The near future goals of geodetic VLBI are to achieve a long-term accuracy of geodetic reference frames on the 1 mm level or better. In this context the consistency of the reference frames and the EOP is of major concern and requires rigorous analysis solutions (Schuh et al. 2004). A holistic approach for the planning of observation sessions and the corresponding rigorous data analysis is desirable. However, it will require further development of the geodetic VLBI technique as such, and the establishment of additional radio telescopes (Petrachenko et al. 2004).

One goal concerning the terrestrial reference frame is for example an improved treatment of periodic and aperiodic effects in order to achieve a more robust reference frame. This is related to the question of geodynamical modeling. For the celestial reference frame one goal is to densify the radio source catalogue and to observe also weaker sources. Of particular interest is the connection between the quasi-inertial reference frames and the dynamical reference frames.

Besides pure reference frame investigation, other goals are to intensify the investigation of a number of geodynamical phenomena. Among these are for example processes in the earth interior that are related to Free Core Nutation (FCN) and Free Inner Core Nutation (FICN). The investigations will require improvements in the data modeling in order to be able to increase sensitivity for these phenomena. Also the question of the earth's free oscillations is of increasing importance in the geodynamical context.

A better understanding of the governing geodynamical mechanisms that cause EOP variations in the sub-diurnal frequency band is another important research topic. One approach to this research is to resolve high-frequency EOP from continuous VLBI observations with large and geometrically well distributed networks.

Further information on new goals for geodetic VLBI can be found for example in Schuh et al. (2004).

9. Necessary future developments

Further development of the geodetic VLBI technique is necessary in order to be able to address the new scientific goals and to contribute to improvements of today's scientific achievements. This development has to fight current limitations in technology, data modeling, and data analysis.

One technical limitation of today's geodetic VLBI observations and data analysis is the increasing amount of radio fre-

quency interference (RFI) caused by communication operators. Both satellite based and ground based communication links disturb in particular the S-band observations and endanger the possibility to compensate for ionospheric effects with the current S/X-frequency set-up used in geodetic VLBI. Thus, there are considerations in the IVS to modify the geodetic frequency set-up (Petrachenko et al. 2004). Observations in the S/X bands will have to be continued in order to guarantee continuity for the existing ICRF, but both, lower and higher observing frequencies could be added.

Higher frequency observations in the K-band could effectively avoid the interference problems. Another advantage of higher frequency observations is that the radio sources at these frequencies appear to have less source structure (Boboltz et al. 2004).

Lower frequency observations in the L-band could allow also to observe signals of Global Navigation Satellite Systems (GNSS) and in that way contribute to a combination of geodetic space techniques and the integration of quasi-inertial and dynamical reference frames.

Observations at frequencies near the water vapor absorption line might allow using the VLBI telescopes directly as line-of-sight water vapor radiometers. These measurements could be used to compensate directly for tropospheric propagation effects instead of using other external information (Petrachenko et al. 2004).

The possible change in the frequency set-up will require development of the geodetic VLBI hardware. It also has to be reflected in the analysis software packages. More details on plans for a modified frequency set-up for geodetic VLBI can be found in Petrachenko et al. (2004).

Another more or less technical limitation is the described loss of phase coherence that makes it impossible to use phase delay observables. Proposals to solve this problem aim also at observing at more than two frequencies simultaneously and at using a pair of telescopes at each site (Petrachenko et al. 2004). A technical development according to these ideas will of course require developing corresponding analysis strategies and to extend the existing analysis software.

A technical development that is currently ongoing is intercontinental real-time e-VLBI. Real-time observations of for example EOP are interesting for reference frame research and applications for navigation. It is anticipated that such real-time observations can be performed on a regular basis in the near future. Thus the capability to perform automated analysis in real-time should be added to all the existing data analysis software packages.

10. Conclusions

Today's analysis strategy and data analysis software for geodetic VLBI correspond to current observing strategy and accuracy of the VLBI group delay observables. This set-up exploits today's resources in a nearly optimum way. Interesting and important geophysical and geodynamical results can be derived from geodetic VLBI data analysis. However, some improvements in the fields of data modeling and statistical methods are necessary even for today's observations.

In order to live up to the future scientific expectations and in order to address new scientific goals in geodetic VLBI, further development is necessary. Technical development is required in order to reach higher precision of the VLBI observables. The analysis strategy will have to correspond to possible changes in observing strategies and for example concentrate primarily on global analysis in a holistic set-up of observing sessions. The analysis software packages need to be developed further and improvement in data modeling and statistical methods have to be incorporated. Also the general ability to perform automated analysis in real-time, and to analyze additional observing frequencies has to be added.

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